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(54) **SECURE COMPUTING ENVIRONMENTS WITH KEY MANAGEMENT FOR PRIVATE COMMUNICATION OVER DATA NETWORKS**

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H04L 9/32 (2006.01)

(52) **U.S. Cl.**
CPC ***H04L 9/0825*** (2013.01); ***H04L 9/0866*** (2013.01); ***H04L 9/3263*** (2013.01)

(58) **Field of Classification Search**
USPC 713/171
See application file for complete search history.

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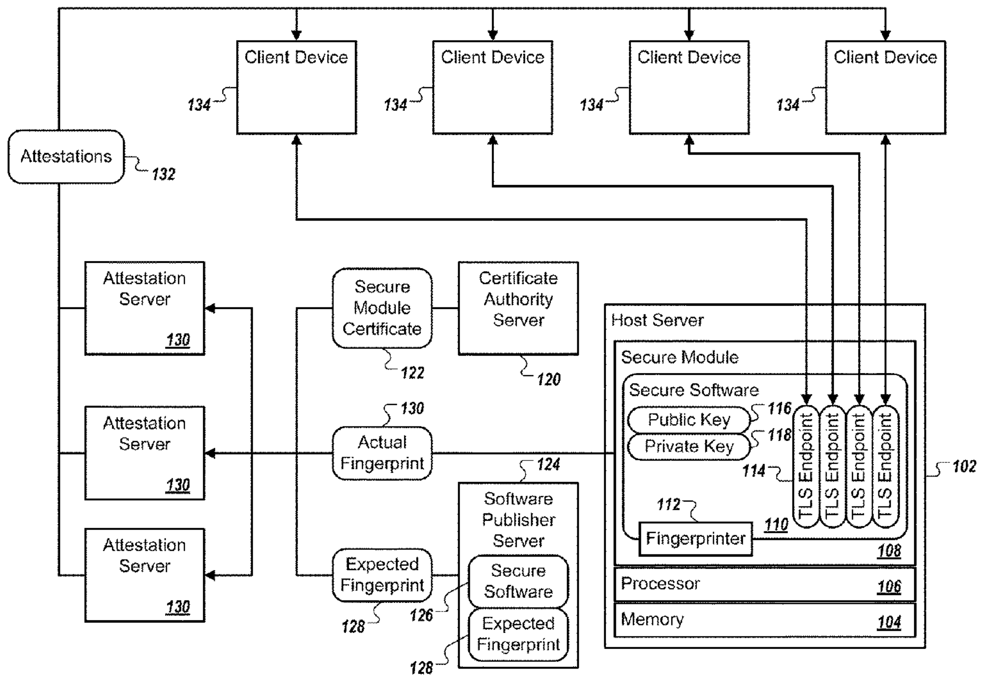
(57) **ABSTRACT**

A secure module can be configured to: provide the trusted execution environment; and load secure-software for processing in the trusted execution environment to perform operations. The operations can include generating a private key and a corresponding public key; maintaining the private key in the trusted execution environment; receiving at least one attestation request from at least one attestation server; responding to the received attestation requests with attestation responses generated with the private key; initiating encrypted connections with client devices using the private key, the encrypted connections having an endpoint within the trusted execution environment such that contents of the encrypted connections are secure from observation and manipulation by other operations outside of the secure module and outside of the client devices; and communicating data with the client devices through the encrypted connections.

20 Claims, 8 Drawing Sheets



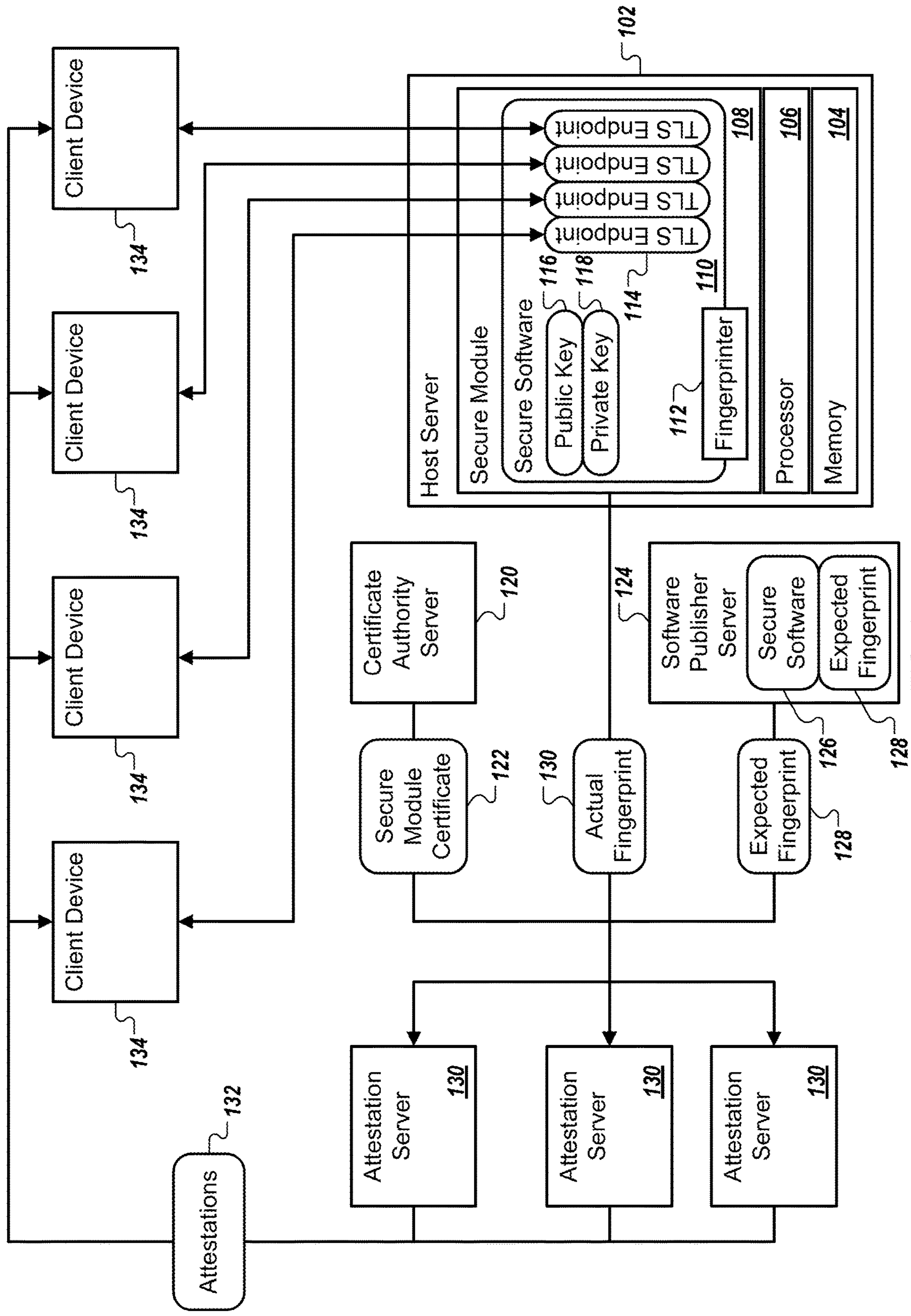

Host Server
102
Secure Module
108
Secure Software
110
Public Key
116
Private Key
118
TLS Endpoint
TLS Endpoint
TLS Endpoint
TLS Endpoint
114
Fingerprinter
112
Processor
106
Memory
104
Certificate Authority Server
120
Secure Module Certificate
122
124
Actual Fingerprint
130
Software Publisher Server
Secure Software
126
Expected Fingerprint
128
Expected Fingerprint
128
Attestation Server
130
Attestation Server
130
Attestation Server
130
Attestations
132
Client Device
134
Client Device
134
Client Device
134
Client Device
134

FIG. 1

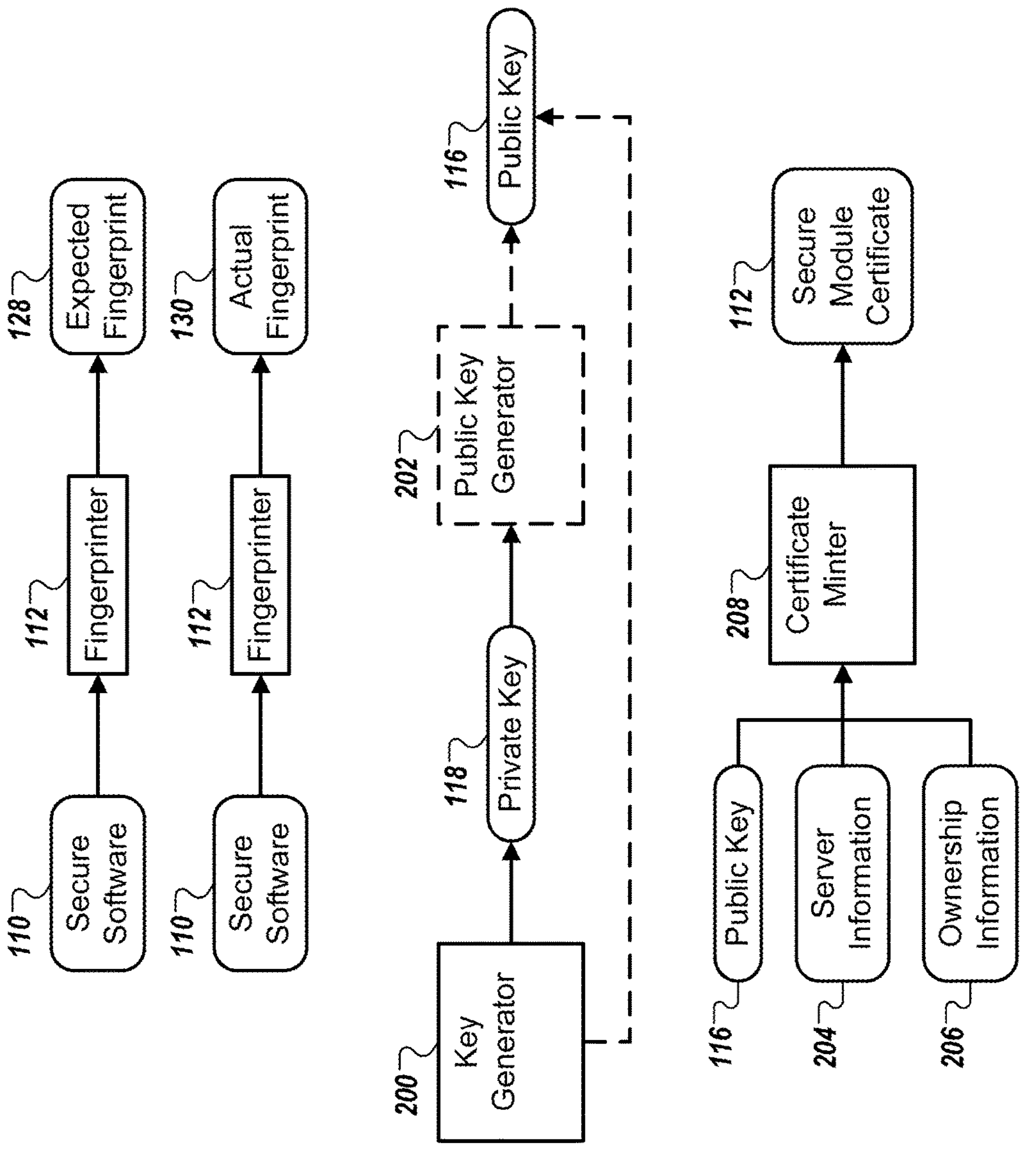

110 Secure Software
112 Fingerprinter
128 Expected Fingerprint
110 Secure Software
112 Fingerprinter
130 Actual Fingerprint
200 Key Generator
118 Private Key
202 Public Key Generator
116 Public Key
116 Public Key
204 Server Information
206 Ownership Information
208 Certificate Minter
112 Secure Module Certificate

FIG. 2

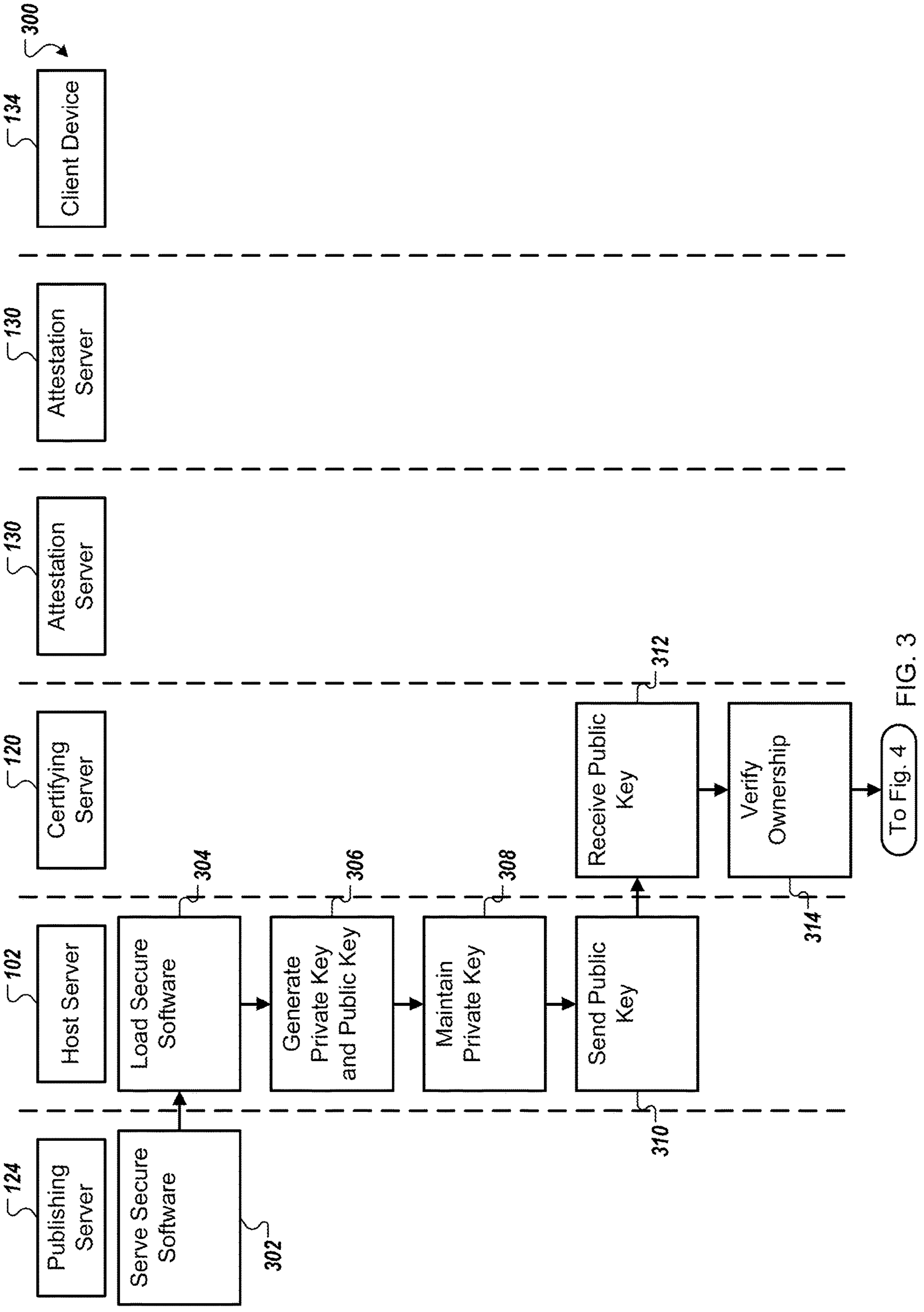

300
124 Publishing Server
102 Host Server
120 Certifying Server
130 Attestation Server
130 Attestation Server
134 Client Device
Serve Secure Software
302
Load Secure Software
304
Generate Private Key and Public Key
306
Maintain Private Key
308
Send Public Key
310
Receive Public Key
312
Verify Ownership
314
To Fig. 4

FIG. 3

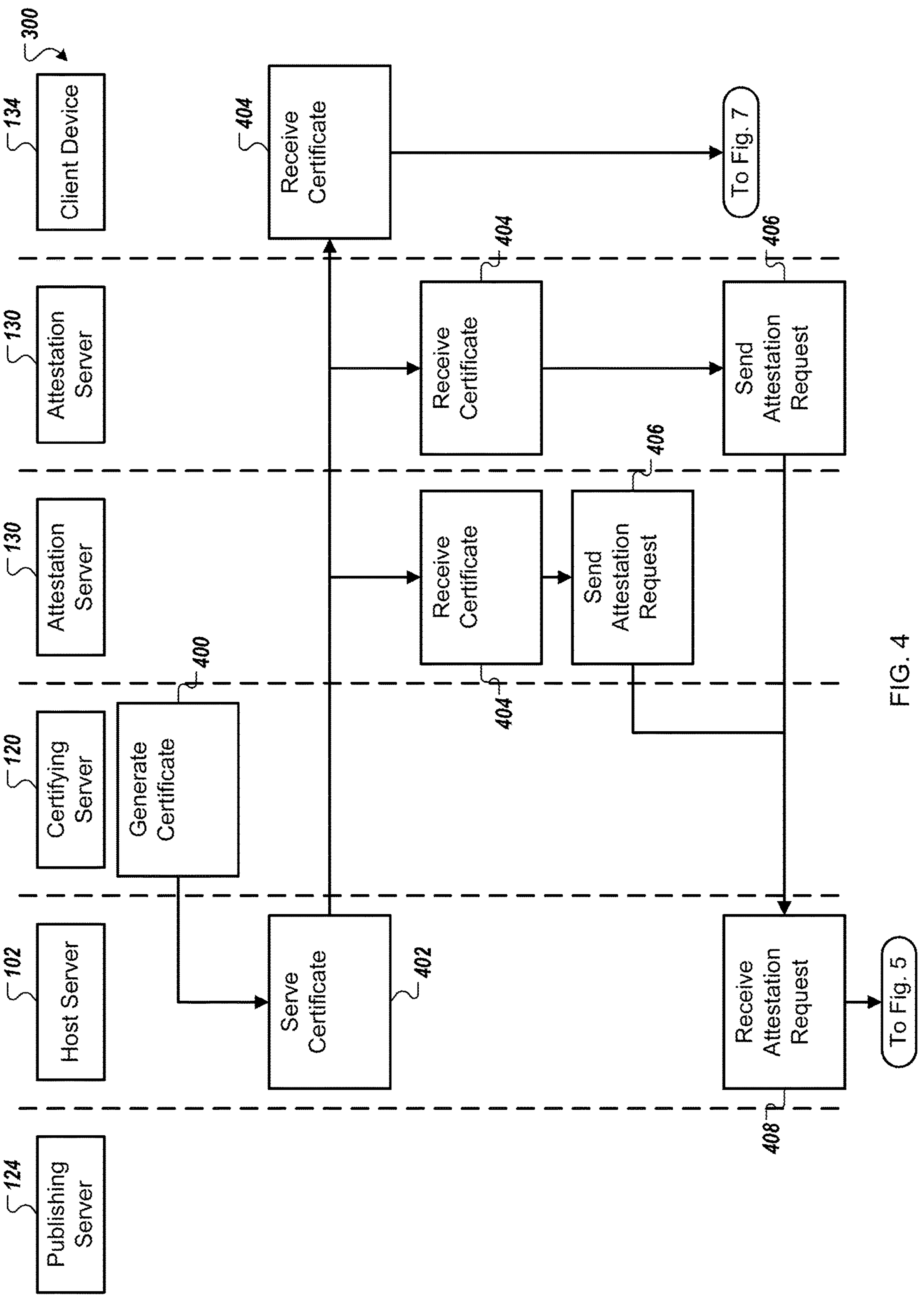

300
134
Client Device
130
Attestation Server
130
Attestation Server
120
Certifying Server
102
Host Server
124
Publishing Server
400
Generate Certificate
402
Serve Certificate
404
Receive Certificate
404
Receive Certificate
404
Receive Certificate
406
Send Attestation Request
406
Send Attestation Request
408
Receive Attestation Request
To Fig. 7
To Fig. 5

FIG. 4

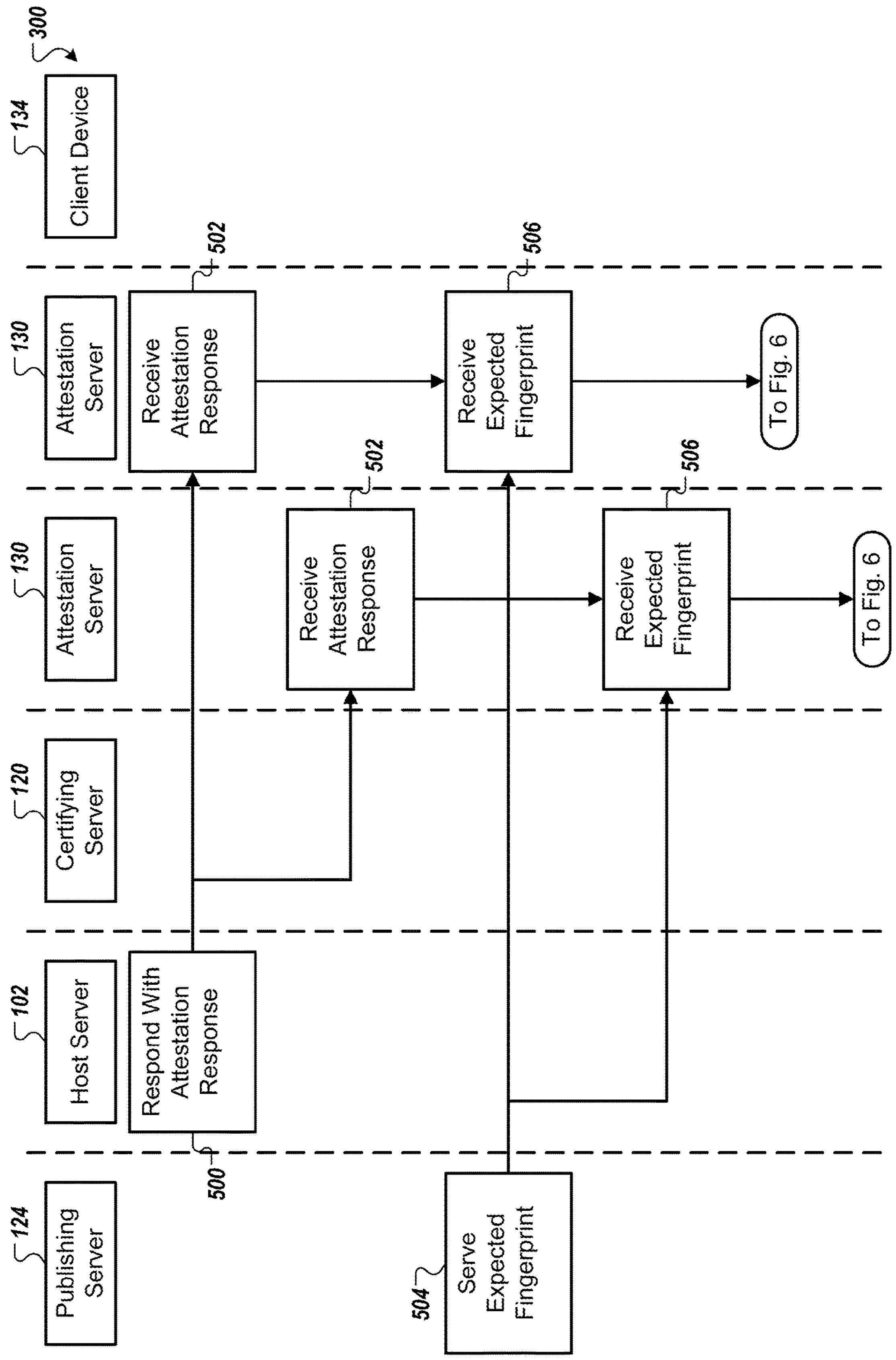

300
Publishing Server 124
Host Server 102
Certifying Server 120
Attestation Server 130
Attestation Server 130
Client Device 134
Respond With Attestation Response 500
Receive Attestation Response 502
Receive Attestation Response 502
Serve Expected Fingerprint 504
Receive Expected Fingerprint 506
Receive Expected Fingerprint 506
To Fig. 6
To Fig. 6

FIG. 5

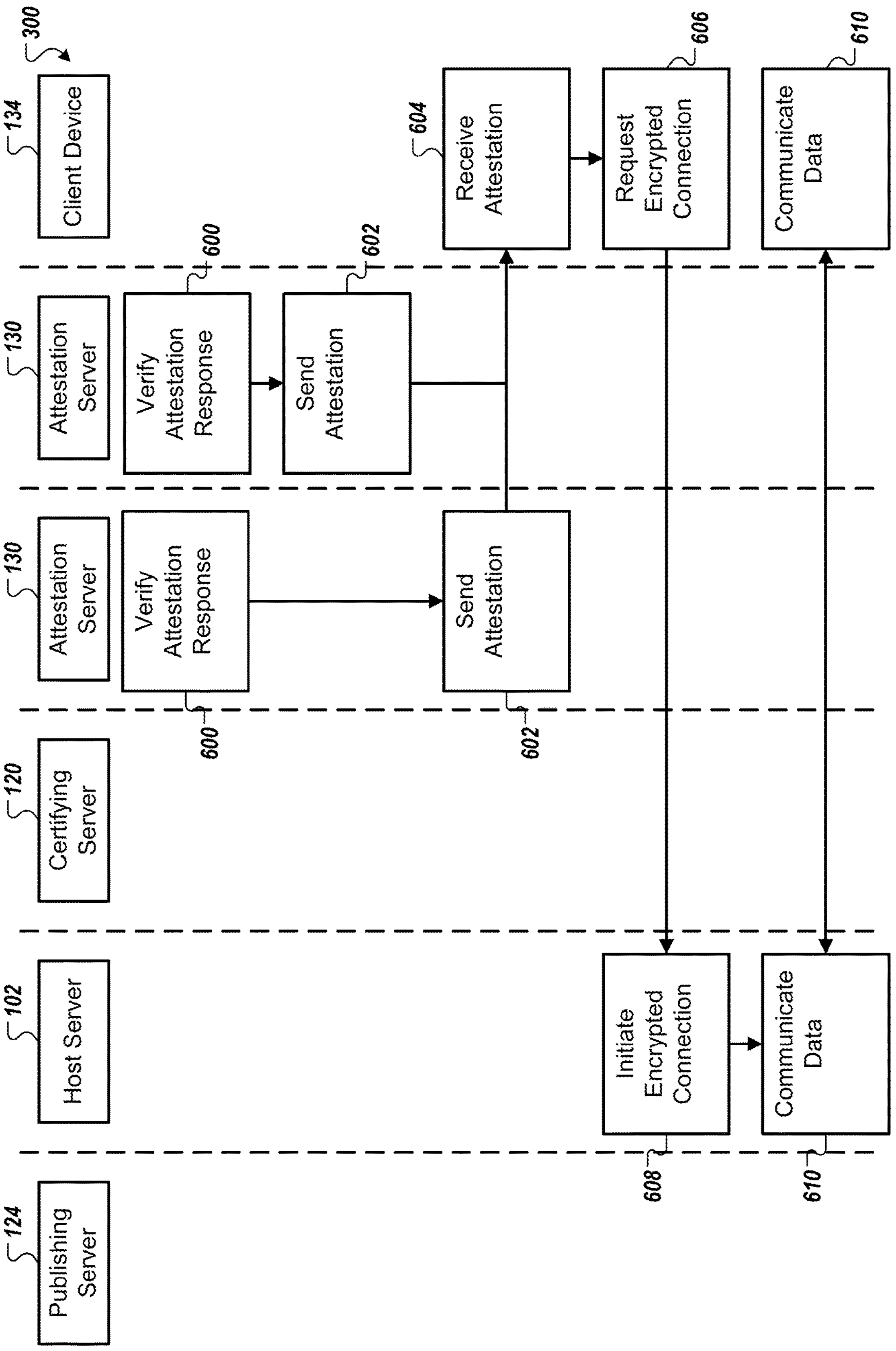

300
Publishing Server
124
Host Server
102
Certifying Server
120
Attestation Server
130
Attestation Server
130
Client Device
134
Verify Attestation Response
600
Send Attestation
602
Verify Attestation Response
600
Send Attestation
602
Receive Attestation
604
Request Encrypted Connection
606
Initiate Encrypted Connection
608
Communicate Data
610
Communicate Data
610

FIG. 6

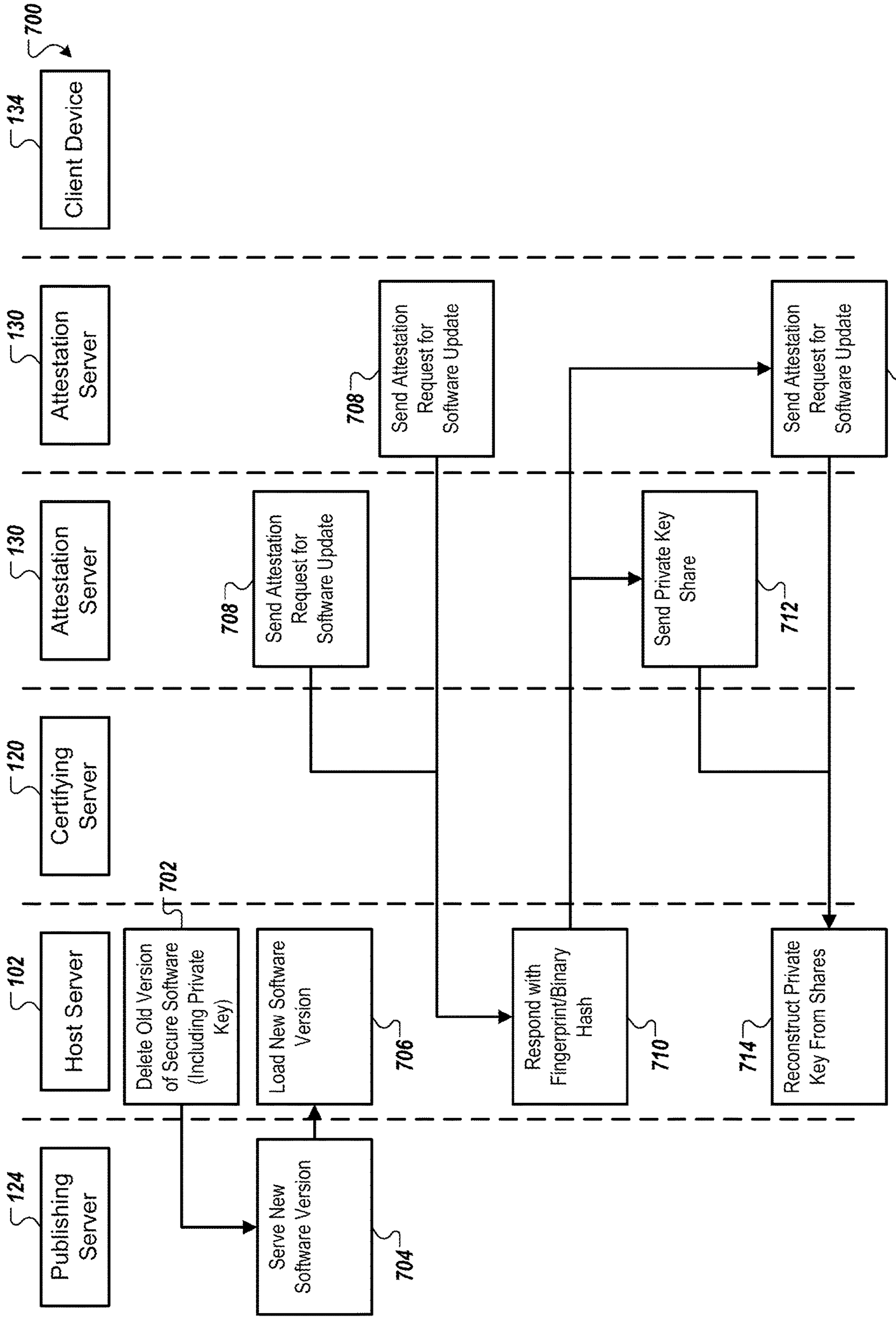

700
Publishing Server
124
Host Server
102
Certifying Server
120
Attestation Server
130
Attestation Server
130
Client Device
134
Delete Old Version of Secure Software (Including Private Key)
702
Serve New Software Version
704
Load New Software Version
706
Send Attestation Request for Software Update
708
Send Attestation Request for Software Update
708
Respond with Fingerprint/Binary Hash
710
Send Private Key Share
712
Send Attestation Request for Software Update
712
Reconstruct Private Key From Shares
714

FIG. 7

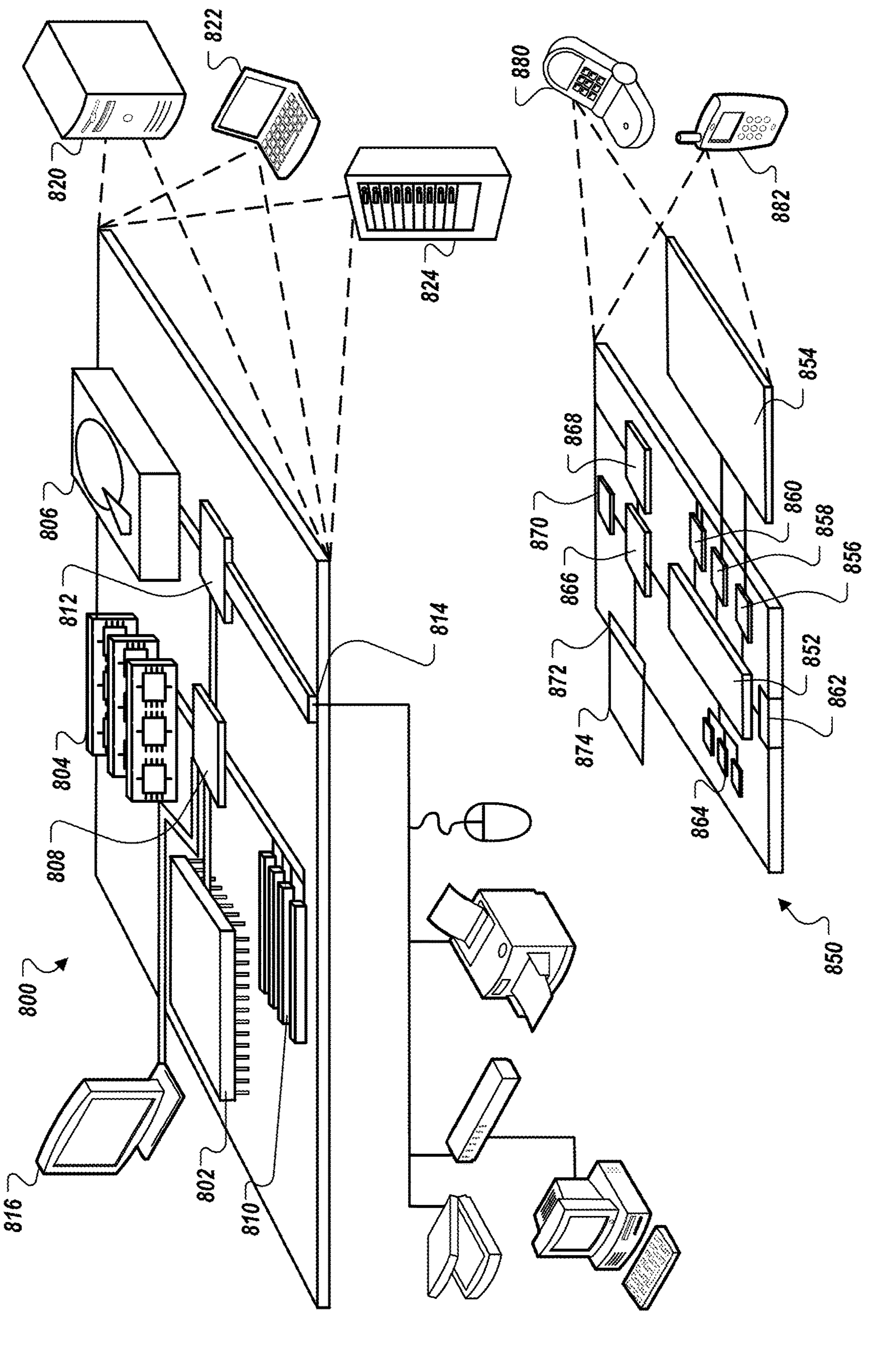

800
802
804
806
808
810
812
814
816
820
822
824
850
852
854
856
858
860
862
864
866
868
870
872
874
880
882

FIG. 8

SECURE COMPUTING ENVIRONMENTS WITH KEY MANAGEMENT FOR PRIVATE COMMUNICATION OVER DATA NETWORKS

FIELD

The present document generally relates to secure computing environments and key management technology for network communication with clients of the secure computing environments.

BACKGROUND

Secure computing environments have been developed, which can protect various aspects of processes within the secure computing environments from observation, detection, or manipulation by third party actors (e.g., malware). For example, secure computing enclaves have been developed that include hardware components of computing devices that provide operations to execute code in an encrypted environment that can shield the operations and/or data being processed from third party actors. For instance, a computing device can include one or more specialized processors that are configured to allow user-level and/or operating system code to define private and encrypted regions of memory, sometimes called enclaves.

Data communication over data networks between two machines can be protected by cryptographic techniques to hide the data being passed by the machines. In some cases, a client and server can exchange information after exchanging or agreeing on an encryption key and a cypher to use when encrypting data. Many web browsers in use support this type of encrypted communication, as do other types of applications.

SUMMARY

The disclosed technology is generally directed to secure and trustworthy computing environments in which a client wishes to have secure communication with an application or code that is executed within a secure environment (e.g., enclave) of a server. When the secure environment is hosted on a typical server (i.e. a server with operations that are not demonstrated to respect private data, which is the case for many servers even if they are not performing any malicious activities), this technology can nevertheless prevent the server from accessing the plaintext of communications between clients and those processes in the secure environment.

Code published and validated by the client—or by a source that the client trusts—can include instructions to generate a random public-private key pair. The code can preserve the private key inside the secure computing environment. Then, clients can be sure that the private key will never be transmitted outside of the secure computing environment, because validation of the code can include a check to ensure that this key is held correctly in the secure environment. The client may then initiate a secure data connection using the public key of the pair, sending the initiation message to the server hosting the secure computing environment. The server's processes outside of the secure environment, not having access to the private key, are thus unable to 'spoof' the secure environment (e.g., maliciously respond to the request pretending to be operating within the enclave to gain access to the plaintext of the communications). Instead, the server passes the encrypted

data into the secure computing environment where it can be decrypted and acted upon. In order to communicate with the processes in the enclave, the client can access the public key from a certificate authority and then initiate, for example, a Transport Layer Security (TLS) or Secure Sockets Layer (SSL) connection with the public key.

A system of one or more computers can be configured to perform particular operations or actions by virtue of having software, firmware, hardware, or a combination of them installed on the system that in operation causes or cause the system to perform the actions. One or more computer programs can be configured to perform particular operations or actions by virtue of including instructions that, when executed by data processing apparatus, cause the apparatus to perform the actions. One general aspect includes a system for providing secure data transfer with a trusted execution environment. The system includes a host server that may include: one or more processors, computer memory, and a secure module configured to: provide the trusted execution environment within which processing is secure from observation and manipulation by other operations outside of the secure module; and load secure-software for processing in the trusted execution environment, the secure-software comprising instructions that, when executed in the trusted execution environment, cause the secure module to perform operations. The operations can include generating a private key and a corresponding public key; maintaining the private key in the trusted execution environment; receiving at least one attestation request from at least one attestation server; responding to the received attestation requests with attestation responses generated with the private key; initiating encrypted connections with client devices using the private key, the encrypted connections having an endpoint within the trusted execution environment such that contents of the encrypted connections are secure from observation and manipulation by other operations outside of the secure module and outside of the client devices; and communicating data with the client devices through the encrypted connections. Other embodiments of this aspect include corresponding computer systems, apparatus, and computer programs recorded on one or more computer storage devices, each configured to perform the actions of the methods.

Implementations may include one or more of the following features. The system where: the operations further may include sending the public key to a certifying server; and the system further may include the certifying server configured to: receive the public key; verify ownership of the host server; responsive to verifying ownership of the host server, generate a certificate for the host server using the public key; and serving the certificate. The system may include one or more client devices configured to: receive the certificate from the host server; and requesting, using the certificate, initiation of at least one of the encrypted connections. The system further may include an attestation server configured to: receive the certificate from the host server; send at least one attestation request; receive the attestation responses; verify the attestation response; and send, to the client devices, attestations for the secure module. The system further may include a publishing server configured to: serve an expected-fingerprint for the secure-software, the expected-fingerprint being may include a data object generated based on binary data of the secure-software; the attestation server is further configured to: send, to the secure module, a fingerprint request; receive, from the secure module, a fingerprint response may include an actual-fingerprint; and where verifying the attestation response further may include determining that the actual-fingerprint matches the expected-fingerprint; and the secure module is further configured to: receive, from the attestation server, the fingerprint request; generate the actual-fingerprint based on binary data of the secure-software; and send, to the attestation server, the fingerprint response may include the actual-fingerprint. The attestation server is further configured to fail verification of the attestation response when the certificate fails a check or when the actual-fingerprint does not match the expected-fingerprint, or when an invalid trusted execution environment is used by the host server. The publishing server is further configured to serve the secure-software to the secure server. The publishing server is the attestation server. The system the system may include a plurality of attestation servers. Implementations of the described techniques may include hardware, a method or process, or computer software on a computer-accessible medium.

One or more advantages can be recognized from various implementations of the disclosed technology, systems, and methods. For example, secure communications can be provided within a computing environment, which can protect from computer-based attacks such as man-in-the-middle attacks. Operations can be performed using existing certificate infrastructure, allowing for faster and less disruptive implementation of technology requiring updates or changes to typical certificate operations.

Other features, aspects and potential advantages will be apparent from the accompanying description and figures.

DESCRIPTION OF DRAWINGS

FIG. **1** is a diagram of an example system for providing secure data transfer with a trusted execution environment.

FIG. **2** is a diagram of example data that can be used in providing secure data transfer with a trusted execution environment.

FIGS. **3-6** are swimlane diagrams of an example process of providing secure data transfer with a trusted execution environment.

FIG. **7** is a swimlane diagram of an example process for reconstructing private keys after a software upgrade that deletes the private keys from a host server.

FIG. **8** is a schematic diagram that shows an example of a computing device and a mobile computing device.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

The disclosed technology is generally directed to secure software running in a secure module of a server, with features to maintain private keys to ensure communication with client devices is protected from inspection by the server. By creating secure endpoints (e.g., TLS or SSL) inside of the secure module (e.g., enclave) instead of under the control of the server, the client device can confidently share data with the secure software that the user of the system would not want to share with the server.

FIG. **1** is a diagram of an example system **100** for providing secure data transfer with a trusted execution environment. In the system **100**, a host server **102** can contain a processor **104**, memory **106**, and a secure module **108** that can provide a trusted execution environment within which processing is secure from observation and manipulation by other operations outside of the secure module. The processor **106** includes one or more processors that can execute instruction stored in the memory **104** and perform

one or more computations or operations within the server. The secure module **108** can include an enclave, sandbox, or other environment with features to protect data and processes in the enclave from observation or interference, including hardware features not alterable with software execution.

The secure module **108** can load secure software **110** from a storage system outside of the secure module **108**, and data generated with the secure software **110** can be stored in a storage system (e.g., memory **104**, which does not have the security assurances of the secure module **110**) with encryption provided by the secure module **108**. For example, the secure module **108** can be configured to automatically decrypt all data loaded into the secure module **108** and to automatically encrypt all data transferred out of the secure module **108** for persistent storage.

The secure module **112** can include a fingerprinter **112** to generate a fingerprint of the secure software **110**. For example, the fingerprinter **112** can, responsive to a request from the host server **102** or from an external source, generate data based on the secure software **100**. In one example, the fingerprinter can generate a cryptographic of the secure software **110** that is loaded into the secure module **108** to demonstrate, for example, that the secure software **110** is really running in the secure module **108** and has not been surreptitiously replaced by a malicious actor. The fingerprinter **112** can include hardware components to ensure trusted creation of these fingerprints. To provide secure communication with sources outside of the host server **102**, the secure software **110** can create communication endpoints (TLS endpoints in the example shown, but other types of endpoints are possible), for example in response to a communication request received by the secure software **110**. The secure software **110** can also be configured to generate one or more public keys **116** and corresponding private keys **118**. The public/private key pairs **116**/**118** can be used to secure the communications through the endpoints **114**.

A certificate authority server **120** manages certificates for the secure software **110** and for other agents, including those not shown here. For example, the certificate authority server **120** may provide a secure module certificate **122** (e.g., a TLS/SSL certificate) created with the public key **116** that can allow for the requesting of a TLS connection having an endpoint **114**—or any other type of secure communication appropriate for protecting data in transit. In some cases, each endpoint is of the same type (e.g., all TLS, all SSL). In some cases, some of the endpoints are of different types (e.g., some TLS, some SSL).

A software publisher server **124** serves the secure software **110**, for example to the host server **102** and/or to other appropriate sources. In addition, the software publisher server **124** can serve an expected fingerprint **128**, which can be compared to an actual fingerprint **130** created by the fingerprinter **122**. Confirmation that the expected fingerprint **128** and the actual fingerprint **130** match can indicate that the secure module **108** is in fact running the secure software **110** as expected (e.g., and malicious, fraudulent, or outdated software).

Attestation servers **130** can create attestations **132** to document the attestation servers' **130** determinations that the secure module **110** is running the secure software **110** (as opposed to other software). For example, the attestation servers **130** can compare the actual fingerprint **130** to the expected fingerprint **128**. If the actual fingerprint **130** does not match the expected fingerprint **128**, the attestation servers **130** can refrain from generated the attestations **130** and may optionally generate an error message or take another appropriate action. If the actual fingerprint **130** does match the expected fingerprint **128**, the attestation servers can issue attestations **132** documenting the determination that the secure module **110** is running the expected secure software **110**. In some cases, the attestations **132** may include other metadata or payload data. For example, the attestations **132** may include a copy of the secure module certificate **122**, may include timestamp information, etc. While the publisher server **124** is shown separate from the attestation servers **130**, in some configurations one or more servers may operate as both an attestation server **130** and publisher server **124**. It will be understood that different components of the system **100** can be owned, administered, and operated by different entities (e.g., people, organizations). For example, by keeping operation of the publication server **124** and attestation servers **130** in the control of a different entity than runs the host server **102**, users of the client devices **134** can use attestations from the attestation servers **130** to ensure entities other than those running the host server **102** have verified the authenticity of the secure software **102**.

The client devices **134** can receive the attestations to verify that the secure module is running the expected security software **110**. Once verified, the client devices can initiate cryptographically secure data communications with the secure software, creating the TLS endpoints **114** that protect the client devices data from eavesdropping or man-in-the-middle attacks.

The system **100** can be used for a variety of purposes in which one or more users of client devices **134** wish to have secure communication with trustworthy software that is running remote from the client devices **134**. One possible use case involves the running and maintaining of cryptocurrency exchanges within secure modules like the secure module **108**. Such an exchange can be configured to convert and exchange currency in a transaction. For example, the exchange can convert Eth from one user's account to Bitcoin in another user's account. Therefore, when client devices **134** make requests to perform buy or sell orders, the asset pair currency exchange in the secure module **108** can complete the requests within the secure module **108**. The exchange can receive user data (e.g., user accounts), which are associated with each of the users that make requests from the client devices **134** to transact via the enclave exchange. Users can transact with each other even if they have different digital assets on different blockchains. One advantage of this technology is that the client devices **134** can interact with other elements using standard web browsers using standard certificate operations. While some implementations can be created in which custom web browsers (or non-web browser application) interact with the system **100**, it is also possible to create implementations that operate with any web browser from any vendor or developer that conforms to standard, universal protocols.

These secure-module-based exchanges can provide for reconciling and matching transactions faster than traditional blockchain technologies. Using the secure module's **110** environment, users can transact with different digital assets across different chains, including but not limited to Bitcoin, Etherum, ERC20 tokens, and assets from other chains such as AVAX. The users can be buyers and sellers of cryptocurrencies who can trust that the secure software **110**, whose behavior is known or approved of by a trusted authority, can access their private data while other computing systems and elements are unable to do so.

FIG. **2** is a diagram of example data that can be used in providing secure data transfer with a trusted execution environment. For example, the data shown in FIG. **2** can be

used by the system **100** of FIG. **1** and therefore will use the system **100** as the basis of an explanation.

Secure software **110** (shown here twice) can include computer-executable instructions that can be loaded into a secure module such as secure module **108** and executed. The secure software **110** can instructions that, when executed in a trusted execution environment of the secure module **108**, cause the secure module **108** to perform operations The fingerprinter **112** can create identifying data based on the secure software **110**. As explained elsewhere, a copy of the secure software **110** can be fingerprinted when the secure software **110** is being validated, and that can be used as the fingerprint **128**. Later, the fingerprinter **112** (either the same fingerprinter **112** or another fingerprinter **112**) can fingerprint software loaded into the secure module **108** to create the actual fingerprint **130**. If that software is the secure software **110**, the actual fingerprint **130** will be a match for the expected fingerprint (e.g., they both contain the same hash value generated from the same input data and using the same hashing algorithm).

A key generator **200** can include one or more hardware and/or software components of the secure module **108** and/or the host server **102**. The key generator **200** can be used as part of the operations undertaken to generate the public key **116** and the private key **118**. For example, the key generator **200** can generate a large pseudorandom or true-random string of binary digits and apply that string as an input to a function that generates one or both of the keys **116** and/or **118**. In some cases, the key generator **200** can directly generate the private key **118** and the public key **116**. In some cases, the key generator **200** generates only one key (e.g., **118**) and another element (e.g., public key generator **202**) can generate the other key.

A certificate minter **208** may be an element of the certificate authority server **120** or may be independent of the certificate authority server **120**. The certificate minter can mint the secure module certificate **1** based on data about the execution of the secure software **110** in the secure module **108**. This can include a copy of the public key **116**, server information **204** (e.g., domain name or universal resource locator, certificate extensions to be used for communication with the secure software **110**, etc), and ownership information **206** (e.g., metadata or payload data showing control of the host server **102** and/or the secure module **108**). The secure module certificate **122** can include one or more certificates or other data that allows for secure communication to the secure software **110** running in the security module **108**. This can include, for example, a copy of the public key **116** in an X.509 certificate.

FIGS. **3-7** are swimlane diagrams of an example process **300** of providing secure data transfer with a trusted execution environment. In some cases, the system **100** can be used to perform the process **300**. Therefore, elements of the system **100** will be used in the description of the process **300**, although other systems may be used to perform the process **300** or similar processes.

The publishing server serves **302** the secure software **110** to the host server **102**. For example, a software package can be developed to run in the secure module **108** and perform a useful activity for client devices **134** and/or users of the client devices. This may include the use and manipulation of sensitive data such as financial data, personally identifying data, health data, etc. To protect this data, the software package may ensure that the sensitive data generated is never exposed outside of the secure module **108** in cleartext form.

Depending on the configuration of the system **100**, the software publishing server **124** may serve the secure software **110** to other requests or may deny requests to serve the secure software **110** to other requests. For example, the developers of the secure software may wish to limit distribution of the code for the secure software **110** and deny service to the attestation servers **130**, the certificate authority **120**, client devices **134**, etc.

The host server **102** loads **204** the secure software **110** for processing in the trusted execution environment **108**. For example, the host server **102** may store the secure software **110** in a particular area of the memory **104** and send a message to the secure module **108** to read that memory address and being execution, storage in another location within the secure module **108**, etc.

The host server **102** generates **306** a private key **118** and a corresponding public key **116** and the host server **102** maintains **308** the private key **118** in the trusted execution environment of the secure module **108**. For example, the secure module can run the key generator **200** (and other elements such as the public key generator **202** or a private key generator) to create the public key **116** and the private key **118**. The secure software **110** running in the secure module **108** may use these keys **116** and **118**. Then, when they are to be saved for long term storage, they may be encrypted into different data (i.e. cyphertext) before the different data is stored to the memory **104**. For example, to maintain the private key **118**, the host server **108** can encrypt the key using a secret that is specific to hardware (e.g., a CPU, a read-only memory module) of the host server **102**. This encrypted private key **118** can be split and backed up to other machines (e.g., the attestation servers **130**), allowing the reconstruction of the private key **118** at a later time (e.g., see FIG. **7**).

The host server **102** sends **310** the public key **116** to a certifying server **120** and the certifying server **120** receives **312** the public key **116**. For example, the public key **116** can be exposed by the secure software **110** for use by other elements of the system **100**. As the private key **118** is not similarly exposed, the public key **116** can be used to create encrypted messages to the secure software **110** that cannot be decrypted by any element **100** other than the secure software **110**. This private key counterpart can be generated and accessed only by the process running within the secure module **108**. By not exposing his private key (even not to an administrator user of the host server **102**) the domain used by the service can be protected from malicious appropriation.

The certifying server **120** verifies **314** ownership of the host server **102**. Responsive to verifying ownership of the host server **102**, the certifying server **120** generates **400** a certificate **122** for the host server **102** using the public key **116**. For example, the certifying server **120** can use the public key **116**, the server information **204**, and/or the ownership information **206** to determine that the request is authorized according to the rules used by the certifying server **120**. This can include determining that a server at a particular domain has modified a data file, accessing and examining ownership records, receiving authorization from a user associated with the certificate authority who has investigated this ownership, etc. Then, the certifying server **120** can use the certificate minter to generate the certificate **122** and transmit the certificate **122** to the host server **102**.

The host server **102** serves **402** the certificate. The attestation servers **130** and the client devices **134** receive **404** the certificate **122** from the attestation server **130**. For example, these elements of the system may each individually and separately request the certificate **122**, or the certificate authority server **120** can initiate transmission without receiving such requests.

The attestation servers **130** send **406** attestation requests to the host server **102**. The host server **102** receives **408** the attestation request from at least one attestation server **130**. For example, the attestation requests may be used to request information from the host server **102** such that the attestation servers **130** can each independently determine if the secure module **108** is running the secure software **110** or some other, unexpected software.

The host server **102** responds **500** to the received attestation requests with attestation responses generated with the private key **118**. The attestation servers **130** receive **502** attestation responses. For example, the host server **102** generates the actual-fingerprint **130** based on binary data of the secure-software **110** and sends the response **500** including the actual-fingerprint **130**.

The publishing server **124** serves **504** an expected-fingerprint **128** for the secure-software **110** and the attestation servers **130** receive the expected-fingerprint **128**. For example, the expected-fingerprint being comprising of a data object generated based on binary data of the secure-software. This can include, for example, a hash of the secure software **110**.

The attestation servers **130** are configured to verify **600** the attestation response. For example, the attestation servers **130** can compare the actual fingerprint **130** to the expected fingerprint **128**. Verifying the attestation response can include determining that the actual-fingerprint matches the expected-fingerprint and passing verification upon determination of a match and failing when the certificate fails a check or when the actual-fingerprint does not match the expected-fingerprint

The attestation servers **130** are configured to send **602**, to the client devices **134**, attestations for the secure module **108**. For example, upon successful verification, the attestation servers **130** can initiate a transfer or respond to requests from the client devices **134** by responding with a transfer of attestations **132** that document the successful verification. This can include appropriate payload data and metadata such as a time-stamp of the verification, an expiration time-stamp after which the attestations **132** expires, etc.

The client devices are configured to receive **404** the certificate **122** and receive **604** the attestations and to request **606**, using the certificate **122**, initiation of at least one encrypted connection with the secure software **110**. For example, with this data, the clients **134** may **1**) be sure that the expected software (i.e., secure software **110**) is being run in the secure module **108** and **2**) be sure that their messages to the secure software **110** will not be available to any other element because of the security provided by TLS communications (which, it will be noted, is not theoretically perfect security but has been demonstrated to be sufficient for many real-world applications). Implementations can advantageously be arranged so that the previous remote-attestation operations only need to be performed once to lean and confirm certificate information and demonstrate that private information (e.g., private or secret keys) is never exposed outside of the secure module **108**. After that, the client devices can use normal secure connections (e.g., SSL, TLS) and as long as the connection is properly configured and secured with the certificate as presented during attestation, client device can operate with confidence that the connection is encrypted and only the secure module **108** can perform the encryption/decryption with the private information (e.g., private or secure keys).

The host server **102** initiates **608** an encrypted connection. The host server **102** and the client device **134** communicate **610** data through the encrypted connection. For example, the secure software **110** can respond to the requests from the client devices **134** by creating one or more TLS endpoints **114** or other types of endpoints (SSL, CurveCP, Kerberos). This allows for use of encrypted connections with client devices using the private key, the encrypted connections having an endpoint within the trusted execution environment such that contents of the encrypted connections are secure from observation and manipulation by other operations outside of the secure module and outside of the client devices.

FIG. **7** is a swimlane diagram of an example process **700** for reconstructing private keys after a software upgrade that deletes the private keys from a host server. For example, when the host server **102** updates the secure software **110** to a new, known-good version, the private key **118** may be lost, based on technological features of the secure module **108** that ensure security (e.g., preventing exposure of the private key **118**). Therefore, the process **700**, or a similar process, may be used to maintain the private key in the trusted execution environment, comprising encrypting the private key with a hardware-specific secret for backup and reconstruction as described here.

Each of the attestation servers **130** can be configured to maintain a secret share of the private key **118**. These secret shares maintained by the attestation servers **130** can be configured to be used in combination to regenerate the private key **118**. For example, the secure software, as part of maintaining the private key **308**, can split the data of the private key into shards (e.g., one shard for each attestation server **130**), encrypt each shard with a secret that is specific to hardware (e.g., a CPU, a read-only memory module) of the host server **102**, and send each encrypted shard to one attestation server **130**.

The host server **102** deletes an old version of the secure software, including private keys **702**. For example, the operator (e.g. human user) of the host server **102** may determine that the host server **102** should upgrade the secure software **110** to a new version that, for example, increases efficiency, provides new functionality, etc. In another example, the host server **102** may receive a notification that the publishing server **124** has a new version available for upgrade, and initiate the upgrade without specific user input. To make room for the new software, the host server **102** can delete the secure software **110**.

The publishing server **124** serves a new version of the software **704**. For example, the publishing server **124** can send one or more data files with the new version of secure software **110**. As will be appreciated, other examples may include the operation **704** being performed before the operation **702**, which may be preferable to limit the length of downtime for the upgrade. However, performing operation **702** before **704** may be preferable to halt the operation of the secure software **110**, for example if a software exploit is found.

The host server **102** loads the new version of the software **706**. For example, the host server **102** can load the new secure software **110** into the secure module **108**. In some cases, this process can include a check or flag to determine if this is a fresh install or a software upgrade. For fresh installs, the secure software can generate the keys as described in **306**. For software upgrades, the process **700** can continue.

The attestation servers **103** send attestation requests for the software update **708**. For example, the host server **102** can send a notification to the attestation server **130**, the publisher server **124** can send a notification to the attestation servers **130**, or another operation can be used by the attestation servers **130** to determine that attestation requests should be sent to the host server **102**. In some cases, these attestation requests in **708** are the same attestation requests described in **406**. In some cases, these attestation requests in **708** are different than the attestation requests in **406**. For example, the attestation requests and/or replies may include a data field to indicate if the attestation process is for an upgrade or a fresh install.

The host server **102** response with hash data **710**. For example, the host server **102** can request, from the secure module **108**, the hash data. In some cases, this hash data is created from a hash of input that includes a fingerprint or other secret that is specific to hardware (e.g., a CPU, a read-only memory module) of the host server **102**. In some cases, this hash data is created from a hash of input that includes binary data of the upgraded secure software **110** (e.g., a hash of the entire executable, of a checksum).

The attestation servers **103** send their private key shares to the host server **102**. For example, the attestation servers **103** can compare the hash data with expected hash data and, upon a match, determine that the known-good software update that is expected is running in the same secure module **108** as the previous version of the software. Upon such a determination, the attestation servers **103** can send their key share back to the host server **102**.

The host server **102** reconstructs the private key(s) from the key shares **714**. For example, the host server **102** can provide the key shares to the upgraded secure software **110** in the secure module **108**. The secure software **110** can then decrypt each share and reconstruct the private key **118** from the cleartext.

FIG. **8** shows an example of a computing device **800** and an example of a mobile computing device that can be used to implement the techniques described here. The computing device **800** is intended to represent various forms of digital computers, such as laptops, desktops, workstations, personal digital assistants, servers, blade servers, mainframes, and other appropriate computers. The mobile computing device is intended to represent various forms of mobile devices, such as personal digital assistants, cellular telephones, smart-phones, and other similar computing devices. The components shown here, their connections and relationships, and their functions, are meant to be exemplary only, and are not meant to limit implementations of the inventions described and/or claimed in this document.

The computing device **800** includes a processor **802**, a memory **804**, a storage device **806**, a high-speed interface **808** connecting to the memory **804** and multiple high-speed expansion ports **810**, and a low-speed interface **812** connecting to a low-speed expansion port **814** and the storage device **806**. Each of the processor **802**, the memory **804**, the storage device **806**, the high-speed interface **808**, the high-speed expansion ports **810**, and the low-speed interface **812**, are interconnected using various busses, and can be mounted on a common motherboard or in other manners as appropriate. The processor **802** can process instructions for execution within the computing device **800**, including instructions stored in the memory **804** or on the storage device **806** to display graphical information for a GUI on an external input/output device, such as a display **816** coupled to the high-speed interface **808**. In other implementations, multiple processors and/or multiple buses can be used, as appropriate, along with multiple memories and types of memory. Also, multiple computing devices can be connected, with each device providing portions of the necessary operations (e.g., as a server bank, a group of blade servers, or a multi-processor system).

The memory **804** stores information within the computing device **800**. In some implementations, the memory **804** is a volatile memory unit or units. In some implementations, the memory **804** is a non-volatile memory unit or units. The memory **804** can also be another form of computer-readable medium, such as a magnetic or optical disk.

The storage device **806** is capable of providing mass storage for the computing device **800**. In some implementations, the storage device **806** can be or contain a computer-readable medium, such as a floppy disk device, a hard disk device, an optical disk device, or a tape device, a flash memory or other similar solid state memory device, or an array of devices, including devices in a storage area network or other configurations. A computer program product can be tangibly embodied in an information carrier. The computer program product can also contain instructions that, when executed, perform one or more methods, such as those described above. The computer program product can also be tangibly embodied in a computer- or machine-readable medium, such as the memory **804**, the storage device **806**, or memory on the processor **802**.

The high-speed interface **808** manages bandwidth-intensive operations for the computing device **800**, while the low-speed interface **812** manages lower bandwidth-intensive operations. Such allocation of functions is exemplary only. In some implementations, the high-speed interface **808** is coupled to the memory **804**, the display **816** (e.g., through a graphics processor or accelerator), and to the high-speed expansion ports **810**, which can accept various expansion cards (not shown). In the implementation, the low-speed interface **812** is coupled to the storage device **806** and the low-speed expansion port **814**. The low-speed expansion port **814**, which can include various communication ports (e.g., USB, Bluetooth, Ethernet, wireless Ethernet) can be coupled to one or more input/output devices, such as a keyboard, a pointing device, a scanner, or a networking device such as a switch or router, e.g., through a network adapter.

The computing device **800** can be implemented in a number of different forms, as shown in the figure. For example, it can be implemented as a standard server **820**, or multiple times in a group of such servers. In addition, it can be implemented in a personal computer such as a laptop computer **822**. It can also be implemented as part of a rack server system **824**. Alternatively, components from the computing device **800** can be combined with other components in a mobile device (not shown), such as a mobile computing device **850**. Each of such devices can contain one or more of the computing device **800** and the mobile computing device **850**, and an entire system can be made up of multiple computing devices communicating with each other.

The mobile computing device **850** includes a processor **852**, a memory **864**, an input/output device such as a display **854**, a communication interface **866**, and a transceiver **868**, among other components. The mobile computing device **850** can also be provided with a storage device, such as a micro-drive or other device, to provide additional storage. Each of the processor **852**, the memory **864**, the display **854**, the communication interface **866**, and the transceiver **868**, are interconnected using various buses, and several of the components can be mounted on a common motherboard or in other manners as appropriate.

The processor **852** can execute instructions within the mobile computing device **850**, including instructions stored in the memory **864**. The processor **852** can be implemented as a chipset of chips that include separate and multiple analog and digital processors. The processor **852** can provide, for example, for coordination of the other components of the mobile computing device **850**, such as control of user interfaces, applications run by the mobile computing device **850**, and wireless communication by the mobile computing device **850**.

The processor **852** can communicate with a user through a control interface **858** and a display interface **856** coupled to the display **854**. The display **854** can be, for example, a TFT (Thin-Film-Transistor Liquid Crystal Display) display or an OLED (Organic Light Emitting Diode) display, or other appropriate display technology. The display interface **856** can comprise appropriate circuitry for driving the display **854** to present graphical and other information to a user. The control interface **858** can receive commands from a user and convert them for submission to the processor **852**. In addition, an external interface **862** can provide communication with the processor **852**, so as to enable near area communication of the mobile computing device **850** with other devices. The external interface **862** can provide, for example, for wired communication in some implementations, or for wireless communication in other implementations, and multiple interfaces can also be used.

The memory **864** stores information within the mobile computing device **850**. The memory **864** can be implemented as one or more of a computer-readable medium or media, a volatile memory unit or units, or a non-volatile memory unit or units. An expansion memory **874** can also be provided and connected to the mobile computing device **850** through an expansion interface **872**, which can include, for example, a SIMM (Single In Line Memory Module) card interface. The expansion memory **874** can provide extra storage space for the mobile computing device **850**, or can also store applications or other information for the mobile computing device **850**. Specifically, the expansion memory **874** can include instructions to carry out or supplement the processes described above, and can include secure information also. Thus, for example, the expansion memory **874** can be provide as a security module for the mobile computing device **850**, and can be programmed with instructions that permit secure use of the mobile computing device **850**. In addition, secure applications can be provided via the SIMM cards, along with additional information, such as placing identifying information on the SIMM card in a non-hackable manner.

The memory can include, for example, flash memory and/or NVRAM memory (non-volatile random access memory), as discussed below. In some implementations, a computer program product is tangibly embodied in an information carrier. The computer program product contains instructions that, when executed, perform one or more methods, such as those described above. The computer program product can be a computer- or machine-readable medium, such as the memory **864**, the expansion memory **874**, or memory on the processor **852**. In some implementations, the computer program product can be received in a propagated signal, for example, over the transceiver **868** or the external interface **862**.

The mobile computing device **850** can communicate wirelessly through the communication interface **866**, which can include digital signal processing circuitry where necessary. The communication interface **866** can provide for communications under various modes or protocols, such as GSM voice calls (Global System for Mobile communications), SMS (Short Message Service), EMS (Enhanced

Messaging Service), or MMS messaging (Multimedia Messaging Service), CDMA (code division multiple access), TDMA (time division multiple access), PDC (Personal Digital Cellular), WCDMA (Wideband Code Division Multiple Access), CDMA2000, or GPRS (General Packet Radio Service), among others. Such communication can occur, for example, through the transceiver **868** using a radio-frequency. In addition, short-range communication can occur, such as using a Bluetooth, WiFi, or other such transceiver (not shown). In addition, a GPS (Global Positioning System) receiver module **870** can provide additional navigation- and location-related wireless data to the mobile computing device **850**, which can be used as appropriate by applications running on the mobile computing device **850**.

The mobile computing device **850** can also communicate audibly using an audio codec **860**, which can receive spoken information from a user and convert it to usable digital information. The audio codec **860** can likewise generate audible sound for a user, such as through a speaker, e.g., in a handset of the mobile computing device **850**. Such sound can include sound from voice telephone calls, can include recorded sound (e.g., voice messages, music files, etc.) and can also include sound generated by applications operating on the mobile computing device **850**.

The mobile computing device **850** can be implemented in a number of different forms, as shown in the figure. For example, it can be implemented as a cellular telephone **880**. It can also be implemented as part of a smart-phone **882**, personal digital assistant, or other similar mobile device.

Various implementations of the systems and techniques described here can be realized in digital electronic circuitry, integrated circuitry, specially designed ASICs (application specific integrated circuits), computer hardware, firmware, software, and/or combinations thereof. These various implementations can include implementation in one or more computer programs that are executable and/or interpretable on a programmable system including at least one programmable processor, which can be special or general purpose, coupled to receive data and instructions from, and to transmit data and instructions to, a storage system, at least one input device, and at least one output device.

These computer programs (also known as programs, software, software applications or code) include machine instructions for a programmable processor, and can be implemented in a high-level procedural and/or object-oriented programming language, and/or in assembly/machine language. As used herein, the terms machine-readable medium and computer-readable medium refer to any computer program product, apparatus and/or device (e.g., magnetic discs, optical disks, memory, Programmable Logic Devices (PLDs)) used to provide machine instructions and/or data to a programmable processor, including a machine-readable medium that receives machine instructions as a machine-readable signal. The term machine-readable signal refers to any signal used to provide machine instructions and/or data to a programmable processor.

To provide for interaction with a user, the systems and techniques described here can be implemented on a computer having a display device (e.g., a CRT (cathode ray tube) or LCD (liquid crystal display) monitor) for displaying information to the user and a keyboard and a pointing device (e.g., a mouse or a trackball) by which the user can provide input to the computer. Other kinds of devices can be used to provide for interaction with a user as well; for example, feedback provided to the user can be any form of sensory feedback (e.g., visual feedback, auditory feedback, or tactile feedback); and input from the user can be received in any form, including acoustic, speech, or tactile input.

The systems and techniques described here can be implemented in a computing system that includes a back end component (e.g., as a data server), or that includes a middleware component (e.g., an application server), or that includes a front end component (e.g., a client computer having a graphical user interface or a Web browser through which a user can interact with an implementation of the systems and techniques described here), or any combination of such back end, middleware, or front end components. The components of the system can be interconnected by any form or medium of digital data communication (e.g., a communication network). Examples of communication networks include a local area network (LAN), a wide area network (WAN), and the Internet.

The computing system can include clients and servers. A client and server are generally remote from each other and typically interact through a communication network. The relationship of client and server arises by virtue of computer programs running on the respective computers and having a client-server relationship to each other.

While this specification contains many specific implementation details, these should not be construed as limitations on the scope of the disclosed technology or of what may be claimed, but rather as descriptions of features that may be specific to particular embodiments of particular disclosed technologies. Certain features that are described in this specification in the context of separate embodiments can also be implemented in combination in a single embodiment in part or in whole. Conversely, various features that are described in the context of a single embodiment can also be implemented in multiple embodiments separately or in any suitable subcombination. Moreover, although features may be described herein as acting in certain combinations and/or initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination. Similarly, while operations may be described in a particular order, this should not be understood as requiring that such operations be performed in the particular order or in sequential order, or that all operations be performed, to achieve desirable results. Particular embodiments of the subject matter have been described. Other embodiments are within the scope of the following claims.

What is claimed is:

1. A system for providing secure data transfer with a trusted execution environment, the system comprising:

a host server comprising:

one or more processors;

computer memory; and

a secure module configured to:

provide the trusted execution environment within which processing is secure from observation and manipulation by other operations outside of the secure module;

receive secure-software from a publishing server; and

load the secure-software for processing in the trusted execution environment, the secure-software comprising instructions that, when executed in the trusted execution environment, cause the secure module to perform operations comprising:

generating a private key and a corresponding public key;

maintaining the private key in the trusted execution environment;

receiving an attestation request from an attestation server, wherein the attestation request is a request for information used by the attestation server to independently verify whether the trusted execution environment is executing the secure-software;

in response to receiving the attestation request from the attestation server, generating an actual-fingerprint of the secure-software, based on binary data of the secure-software that is being executed by the trusted execution environment, (ii) generating, with the private key, an attestation response that includes the actual-fingerprint of the secure-software, and (iii) sending the attestation response to the attestation server, wherein the attestation server is configured to verify whether the actual-fingerprint of the secure-software matches an expected-fingerprint of the secure-software that has been provided by the publishing server, and to send a verification result to a client device that indicates whether the trusted execution environment is executing the secure-software;

in response to receiving, from the client device, a request for an encrypted connection, initiating the encrypted connection with the client device using the private key, wherein the encrypted connection includes an endpoint within the trusted execution environment such that contents of the encrypted connection are secure from observation and manipulation by other operations outside of the secure module and outside of the client device; and

communicating data with the client device through the encrypted connection.

2. The system of claim **1**, wherein:

the operations further comprise sending the public key to a certifying server; and

the system further comprises the certifying server configured to:

receive the public key;

verify ownership of the host server;

responsive to verifying ownership of the host server, generate a certificate for the host server using the public key; and

serve the certificate.

3. The system of claim **2**, the system further comprising one or more client devices configured to:

receive the certificate from the host server; and

request, using the certificate, initiation of at least one of the encrypted connections.

4. The system of claim **2**, wherein the attestation server is configured to:

receive the certificate from the host server;

send at least one attestation request;

receive attestation responses;

verify the attestation responses; and

send, to client devices, verification results for the secure module.

5. The system of claim **4**, wherein:

the publishing server is configured to:

serve an expected-fingerprint for the secure-software, the expected-fingerprint comprising a data object generated based on binary data of the secure-software; and

the attestation server is further configured to:

send, to the secure module, the attestation request; and

receive, from the secure module, an attestation response comprising the actual-fingerprint of the secure-software.

6. The system of claim **5**, wherein the attestation server is further configured to send a verification result that indicates a failed verification when the certificate fails a check or when the actual-fingerprint does not match the expected-fingerprint, or when an invalid trusted execution environment is used by the host server.

7. The system of claim **5**, wherein the publishing server is further configured to serve the secure-software to the host server.

8. The system of claim **7**, wherein the publishing server is the attestation server.

9. The system of claim **4**, the system comprising a plurality of attestation servers.

10. A computer-readable media for providing secure data transfer with a trusted execution environment, the media tangibly storing instructions that, when executed by a host server, cause a secure module of the host server to:

provide the trusted execution environment within which processing is secure from observation and manipulation by other operations outside of the secure module;

receive secure-software from a publishing server; and

load the secure-software for processing in the trusted execution environment, the secure-software comprising instructions that, when executed in the trusted execution environment, cause the secure module to perform operations comprising:

generating a private key and a corresponding public key;

maintaining the private key in the trusted execution environment;

receiving an attestation request from an attestation server, wherein the attestation request is a request for information used by the attestation server to independently verify whether the trusted execution environment is executing the secure-software;

in response to receiving the attestation request from the attestation server, (i) generating an actual-fingerprint of the secure-software, based on binary data of the secure-software that is being executed by the trusted execution environment, (ii) generating, with the private key, an attestation response that includes the actual-fingerprint of the secure-software, and (iii) sending the attestation response to the attestation server, wherein the attestation server is configured to verify whether the actual-fingerprint of the secure-software matches an expected-fingerprint of the secure-software that has been provided by the publishing server, and to send a verification result to a client device that indicates whether the trusted execution environment is executing the secure-software;

in response to receiving, from the client device, a request for an encrypted connection, initiating the encrypted connection with the client device using the private key, wherein the encrypted connection includes an endpoint within the trusted execution environment such that contents of the encrypted connection are secure from observation and manipulation by other operations outside of the secure module and outside of the client device; and

communicating data with the client device through the encrypted connection.

11. A method for providing secure data transfer with a trusted execution environment, the method comprising:

providing the trusted execution environment within which processing is secure from observation and manipulation by other operations outside of the secure module;

receiving secure-software from a publishing server; and

loading the secure-software for processing in the trusted execution environment, the secure-software comprising instructions that, when executed in the trusted execution environment, cause the secure module to perform operations comprising:

generating a private key and a corresponding public key;

maintaining the private key in the trusted execution environment;

receiving an attestation request from an attestation server, wherein the attestation request is a request for information used by the attestation server to independently verify whether the trusted execution environment is executing the secure-software;

in response to receiving the attestation request from the attestation server, (i) generating an actual-fingerprint of the secure-software, based on binary data of the secure-software that is being executed by the trusted execution environment, (ii) generating, with the private key, an attestation response that includes the actual-fingerprint of the secure-software, and (iii) sending the attestation response to the attestation server, wherein the attestation server is configured to verify whether the actual-fingerprint of the secure-software matches an expected-fingerprint of the secure-software that has been provided by the publishing server, and to send a verification result to a client device that indicates whether the trusted execution environment is executing the secure-software;

in response to receiving, from the client device, a request for an encrypted connection, initiating the encrypted connection with the client device using the private key, wherein the encrypted connection includes an endpoint within the trusted execution environment such that contents of the encrypted connection are secure from observation and manipulation by other operations outside of the secure module and outside of the client device; and

communicating data with the client device through the encrypted connection.

12. The method of claim **11**, wherein:

the operations further comprise sending the public key to a certifying server; and

the certifying server is configured to:

receive the public key;

verify ownership of the host server;

responsive to verifying ownership of the host server, generate a certificate for the host server using the public key; and

serve the certificate.

13. The method of claim **12**, the method further comprising:

receiving, by one or more client devices, the certificate from the host server; and

requesting, by the one or more client devices using the certificate, initiation of at least one of the encrypted connections.

14. The method of claim **12**, the method further comprising:

receiving, by the attestation server, the certificate from the host server;

sending, by the attestation server, at least one attestation request;

receiving, by the attestation server, attestation responses;

verifying, by the attestation server, the attestation responses; and

sending, to client devices, verification results for the secure module.

15. The method of claim **14**, the method further comprising:

serving, by the publishing server, an expected-fingerprint for the secure-software, the expected-fingerprint comprising a data object generated based on binary data of the secure-software;

sending, by the attestation server and to the secure module, the attestation request; and

receiving, by the attestation server and from the secure module, an attestation response comprising the actual-fingerprint of the secure-software.

16. The method of claim **15**, wherein the attestation server is further configured to send a verification result that indicates a failed verification when the certificate fails a check or when the actual-fingerprint does not match the expected-fingerprint, or when an invalid trusted execution environment is used by the host server.

17. The method of claim **15**, wherein the publishing server is further configured to serve the secure-software to the host server.

18. The method of claim **17**, wherein the publishing server is the attestation server.

19. The method of claim **14**, wherein sending, to client devices, verification results for the secure module comprises sending verification results for the secure modules from a plurality of attestation servers.

20. The method of claim **11**, wherein maintaining the private key in the trusted execution environment comprises encrypting the private key with a hardware-specific secret for backup and reconstruction.

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